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**A Description of the Weapon
Optimization and Resource
Requirements Model (WORRM)**

G. E. Koleszar, Project Leader

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PREFACE

This document was prepared by the Institute for Defense Analyses under an amendment to Task Order T-I1-1619, *Analytical Support to Capabilities-Based Munitions Review (CBMR)*, with technical cognizance for this task under the Director for Force Structure, Resources, and Assessment, Joint Staff/J-8, and the Director, Strategic and Tactical Systems, OUSD (A&T). The Project Officers for the task were LtCol Kirk Yost, Joint Staff/J-8, and Mr. Christopher DiPetto, OUSD(A&T)/S&TS. The principal authors of this document were Mr. James N. Bexfield and Dr. Frederic A. Miercort.

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I. INTRODUCTION

The Weapon Optimization and Resource Requirements Model (WORRM) is a campaign level model that represents the attack of Blue aircraft and standoff missiles against a Red ground-based target set and defenses. It assigns Blue platforms and weapons to the Red target set so as to maximize target value destroyed and/or minimize platform attrition. When given a weapons budget and weapons costs, it can be used to determine an optimal weapons mix for the scenario being analyzed. It is formulated as a linear program.

WORRM and its predecessor models have been used in several studies since its formulation in 1990. The first use was to support the *Bottom Up Review (BUR)* in 1991-1992. It was next used in the *1994-1995 Heavy Bomber Force Study*. The model, named the IDA Bomber Force Model (IBFM) at the time, needed significant modifications prior to its acceptance for the *DoD Deep Attack Weapons Mix Study (DAWMS)* that was conducted in 1995-1997. These enhancements included a change in the objective function to maximize target value destroyed; the addition of weather and C4ISR effects; and significant increases in dimensionality for weapon effectiveness, targets, and aircraft attrition. The changes were so significant that IDA decided to rename the model the Weapon Optimization and Resource Requirements Model (WORRM). From 1997-1999, it was used in the *Deep Attack Study (DAS)*, in the *Long Range Interdiction Study*, and in a modified version in a study sponsored by the Decision Support Center to determine the military utility of selected C4ISR capabilities. Currently, the model is undergoing further improvements in the C4ISR area, with the improved version of the model being renamed the Engagement Resources Allocation Model (ERAM).

Chapter II of this document contains a general description of the model, together with comments on data sources and how the model is structured for a typical study. Chapter III contains the mathematical formulation, and Chapter IV describes several special features that the user may find helpful when conducting a study.

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II. GENERAL DESCRIPTION AND DATA SOURCES

A. SCENARIO SETUP AND DIMENSIONALITY

This chapter contains a general description of WORRM. It is a large linear programming model that either maximizes target value destroyed or minimizes platform attrition. It uses the following key constraints:

- Do not kill more targets than are available
- Achieve minimum target damage goals by phase
- Do not exceed weapon inventories
- Do not exceed time-phased availability of resources (sorties/missiles)
- Do not exceed maximum allowable attrition for any platform type.

In the following sections we elaborate on these and others of the model starting with the temporal and spatial characterizations.

1. Temporal Resolution

The time dimension in WORRM allows the user to represent many important aspects of the warfight to include:

- the arrival of forces to the battle
- the minimum target kill goals that must be achieved to meet warfighting objectives in each time period
- a suppression of enemy air defenses (SEAD) campaign that reduces the effectiveness of Red's air defenses (reflected in time dependent per sortie attrition rates)
- weather variations between theaters and weather dependent tactics (e.g., Red may decide to attack in bad weather)
- manage aircraft attrition by not allowing any platform type to "use" all of its allowable attrition in the early phases of the warfight, and

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- the changing values associated with killing targets above the minimum target kill goals (e.g., higher target values may be associated with tanks killed early in the battle).

Typically, WORRM is used to analyze warfighting capabilities in the Defense Planning Guidance (DPG)-based two nearly simultaneous major theater war (MTW) scenario, but it can also be used to model one MTW or selected portions of any size warfight. In a 2-MTW formulation each theater consists of three major phases: Halt, Build and Pound, and Counter-Offensive. The model is currently dimensioned for 10 time periods, divided between these two theaters. The halt phase is usually represented by two or three time periods (where increased fidelity is desired because of its importance in determining whether Red can be halted before it achieves its territorial objectives), the build and pound phase by one period, and the counter-offensive phase by one or two periods.

2. Spatial Resolution

A range-band geographical structure is used to help distinguish between targets with respect to their value, the ground defenses protecting them, the platforms that can reach them, and how well target location is known by the Blue forces. In a typical case, the Red target set is partitioned into four range bands: 0-22, 22-80, 80-180, and 180-400 nautical miles, with the forward line of troops (FLOT) starting at 0. The first range band is often referred to as the close battle area.

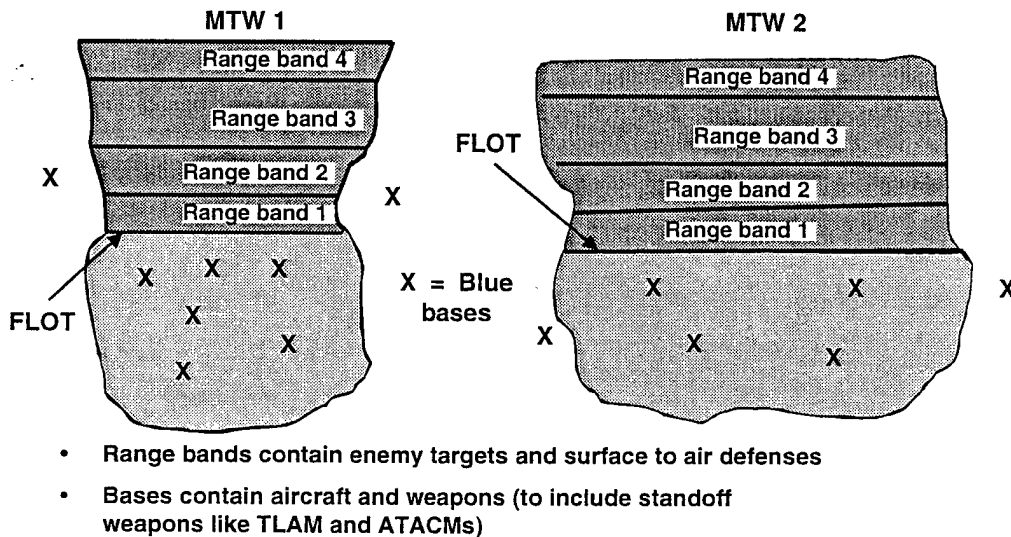


Figure 1. Spatial Representation

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3. Resource Resolution

The targets are described using over 200 target types that reflect DIA Consolidated Target Set categorization. These targets are assigned to one of two target groups: tactical—primarily associated with land forces, and strategic—mostly infrastructure, WMD, and fixed air defenses. The defenses associated with tactical targets are usually relatively short-range and mobile while those associated with strategic targets are most often long-range and fixed.

The model is capable of representing over 30 platform types and over 100 weapon types. These weapon types can be delivered from any one of three delivery altitudes (low, medium, and high) in three weather states (clear, marginal, and adverse).

B. OBJECTIVE FUNCTION

Several objective functions are available to the user. The primary one is to maximize target value destroyed. Each target type is assigned a value that may vary by the phase of the war and by the location of the target (range band). It represents the value to Blue of killing the target. The user can add to the maximize target value objective function penalties for aircraft attrition and/or sorties flown.

Another variation of this option minimizes "weighted" aircraft attrition. The weights could correspond to the replacement costs of the aircraft. This may result in one aircraft type losing a much larger portion of its force than another (e.g., a result could be 20 percent attrition to the A-10 fleet and only 2 percent for the F-16s).

A third option uses an objective function that minimizes a factor used to calculate the attrition bounds for each aircraft type. (In a 2-MTW context, it is the sum of the factors for each MTW.) This option minimizes the number of aircraft lost while maintaining user-defined relative attrition relationships among aircraft types. This is the same as the last formulation except that relative attrition relationships between aircraft types are maintained.

C. TARGET KILL GOALS

The model also incorporates a minimum number of targets that must be killed by Blue in order to achieve warfighting goals, e.g., "win" the war. They are usually derived from inputs provided by the operators or theater CINC staffs and are functions of time period (phase), location (range band), and weather. Requirements exist to kill a

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minimum number of targets in each of the three weather states (e.g., must kill 10 tanks in clear weather, 5 in marginal, and 3 in adverse weather). Operationally, some target types may not need to be attacked in marginal and adverse weather. These target types are given "weather flexibility"—they may be killed in "bad" weather but there is not a firm requirement to do so.

Some destroyed targets may regenerate. The speed with which a target can regenerate and the number of destroyed targets that can be repaired is specified for each target type. Maneuver targets that have been catastrophically killed will not regenerate. A fraction of the targets killed to a fire power or mobility kill criteria usually will regenerate. The model requires Blue to kill all regenerated targets in their regeneration phase. Thus, some targets killed early in the war may regenerate several times before the end of the counter-offensive phase.

D. BLUE RESOURCE LIMITS

The number of weapons that Blue can deliver is limited by the number of platforms in the warfight and the number of sorties they can fly per day. The number of Blue platforms vary by phase and depend on an arrival schedule. The sortie rate depends on the locations of the deployed bases and on the weather. (Sortie rates may be degraded in adverse weather.)

Not all sorties successfully find a target, e.g., they fail to find both their primary and secondary target. In WORRM, this is represented by a mission abort rate. This rate is discussed in more detail in the C4ISR sections. Mission aborted sorties do fly and do suffer attrition commensurate with the target they have been assigned to attack. If they are not attrited and do not strike a secondary target, they bring back their weapons for use at another time.

The next topic concerns the availability of Blue weapons. The total number of weapons available by type that Blue platforms can deliver in the 2-MTW conflict is a user input. It is not a function of phase. Basically, all weapons are assumed to be available where needed to support Blue sorties. In other words, the model assumes that if Blue aircraft are available, then the weapons they would need to prosecute the air war are also available at the same location. When the weapon budget option is used, the weapons available to support Blue sorties is the sum of the inventory weapons allocated to the warfight and the weapons purchased with the budget.

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E. AIRCRAFT ATTRITION

Blue aircraft attrition is "managed." A maximum number of aircraft that can be attrited is specified for each Blue aircraft type. Typically, this maximum number is calculated so that each aircraft type can lose the same fraction of their average in-theater inventory.

Several studies (e.g., DAWMS) have used the following approach to set the aircraft attrition bounds. First, the minimum attrition is computed when just those targets needed to satisfy the minimum target goals are killed. This special formulation of WORRM does not maximize target value—rather it minimizes aircraft attrition while maintaining the relative attrition relationships among platform types. The second step increases these minimum bounds (one for each MTW) by 25 percent and then maximizes target value. This builds in flexibility and helps guard against uncertainties in the attrition calculations.

The per sortie attrition rate input is a function of the platform type, weapon used (overflight and four standoff weapon launch distances), delivery profile (low, medium, and high altitude), target group (strategic or tactical), defense level associated with each target group (light, medium, heavy), target location (range band), and phase of war (lower attrition in later phases). Thus, when a platform is assigned to attack a target with a single sortie it will suffer attrition consistent with the above referenced variables.

Determining the per sortie attrition inputs can involve a complex process. Figure 2 shows the method used to calculate attrition rates for fixed-wing aircraft. Each sortie suffers attrition in accordance with the defenses encountered when attacking its target. The first step is to determine the number of encounters each aircraft type has with each surface-to-air missile (SAM) type for each delivery profile when attacking every target in the database. This is done by representing every SAM site together with its lethal envelope at the locations projected by DIA. The target locations are likewise represented. Then, each aircraft type is assigned to attack each target with its route to the target determined by the IDA Target Accessibility Model (ITAM), a separate preprocessor that provides aircraft encounter data used to calculate attrition rates. The number of encounters with SAMs for this "minimum threat" route is determined for overflight and four standoff range deliveries.

Next, an encounter probability of kill (P_k) is computed using an appropriate shot doctrine, electronic countermeasures (ECM) and maneuver degrade assumptions, and

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SAM lethality. Thus, a P_k is associated with each encounter. These P_k s are compounded to produce an attrition rate for the route. This attrition rate is reduced by a lethal suppression of enemy air defenses (SEAD) factor that varies by phase.

The SEAD adjusted route attrition rates are now aggregated by target group and defense level for each delivery altitude, range band and weapon standoff range. Three defense levels are used:

- Light: can overfly target at high altitude without encountering defenses
- Medium: can fly to within 40 nmi of targets at high altitude without encountering defenses
- Heavy: all other cases

This result is adjusted again to reflect real-world considerations like Red CONOPS and SAM missile inventories via a calibration procedure with the results of a campaign model like TACWAR or Thunder. The calibration is accomplished by adjusting the input attrition rates used in WORRM in a minimum attrition bound run until the output per sortie attrition rates agree with those from TACWAR or Thunder. The end result is a per sortie attrition rate for each platform type, defense level, delivery altitude, weapon standoff range, target group, target location (range band) and phase of the war.

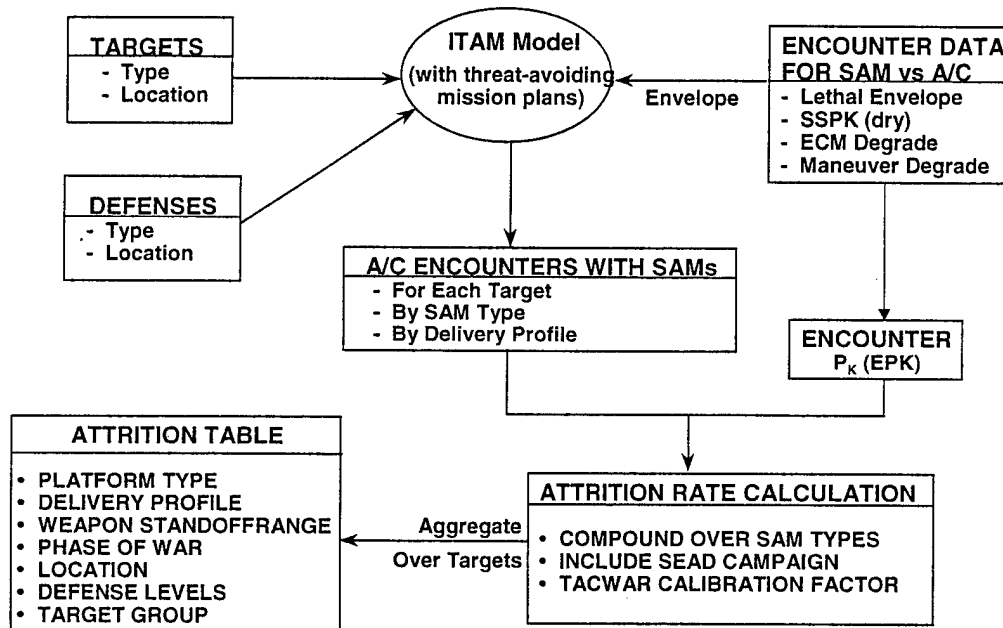


Figure 2. Calculating Attrition Rates (Fixed-Wing Aircraft)

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In summary, the relative values of the attrition rates used in WORRM depend on the defenses encountered enroute to the weapon release points, the lethality of the defenses encountered, and the level of defense suppression achieved by phase. These attrition rates are also adjusted to reflect the results of a two-sided campaign model.

F. WEAPON EFFECTIVENESS

The effectiveness of weapons is based on Joint Munitions Effectiveness Manual (JMEM) calculations that include as inputs the aircraft type, weapon type, weapon load, delivery profile, and target type. Weapon effectiveness also varies by weather. The weapon load could vary by target location (some aircraft carry fewer weapons when attacking distant targets). In one form of the model, the 200 target types mentioned earlier can be further aggregated into 50 classes for the calculation of damage when attacked by Blue weapons. A model based on a clustering process called simulated annealing is used to determine the preferred target classes so as to minimize aggregation errors. A user may wish to operate the model in this aggregated mode when a significantly reduced run time is needed.

G. C4ISR

There are two ways C4ISR impacts the warfight in WORRM. The first way is in the ability of the platform to find the target and deliver its weapons. This, in turn, depends on the capability of offboard sensors like Joint Surveillance and Target Acquisition Radar System (JSTARS) and Unmanned Aerial Vehicles (UAVs) to find targets and provide locations to the weapon delivery platforms. It also depends on the ability of the delivery platform itself to find a target with its onboard sensors. WORRM represents the above aspects of C4ISR with a Target Not Found (TNF) factor that causes the sortie to abort. For fixed targets the onboard sensor drives the probability of detection. For dwell and moving targets both the onboard and offboard sensors are represented in the TNF factor. The manner with which WORRM models aborted sorties was discussed in Section D.

The second way C4ISR impacts the warfight in WORRM is through the effectiveness of the weapon after release. The weapon may have no or reduced effectiveness because it attacked the wrong target (e.g., decoy, target is already dead) or it has an inaccurate aimpoint (which may be partly caused by weather). WORRM represents this aspect of C4ISR by multiplying the weapon effectiveness values by a

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C4ISR degrade factor. This factor is the product of two terms: the Dead-or-Alive Factor (DAF) which reflects attacks against decoys or dead targets and the Target Information Factor (TIF) which measures the quality of information about the target available to the platform at the time of weapon release.

The dimensionality associated with these C4ISR factors is displayed in Figure 3.

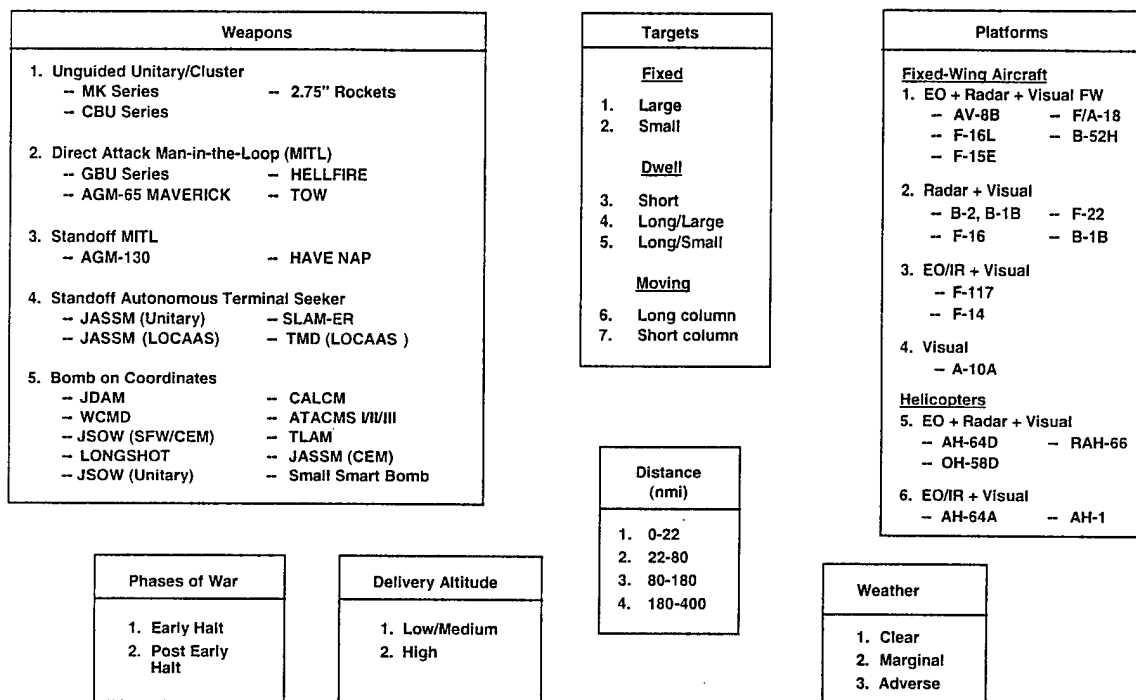


Figure 3. C4ISR Categories (Partial List)

H. PREFERRED WEAPON MIX OPTION

A discussion of weapon inventory constraints appeared at the end of Section D. WORRM can also be used to provide insights into a preferred weapon mix. Two types of constraints are used in this formulation. The first type is the same as the one mentioned in Section D. It places a limit on the number of weapons that can be used by weapon type. In the preferred weapon mix option this limit is on the use of the "existing" inventory of weapons (e.g., those in the 1998 inventory). The second type of constraint is the weapon budget. Unit costs are provided for each weapon type that can be purchased. Each weapon purchased then uses a part of the limited budget. In this configuration, the

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linear program determines both the best use of inventory weapons and the best mix of "buy" weapons so as to optimize the objective function (e.g., maximized target value destroyed or minimize platform attrition) .

I. CODE IMPLEMENTATION

WORM is written in Fortran and uses a commercial linear program solver called CPLEX. It is implemented on SUN workstations. Run times for a 2-MTW scenario vary from about 2 hours on a SUN ULTRA to 14 hours on a SUN SPARC 2. A typical 2-MTW case may generate up to 1,500,000 variables.

J. OUTPUT REPORTS

WORM also has an extensive set of output reports. The following list describes a few of them:

- Weapons (U.S. only or may include Allies)
 - Weapons purchased
 - Weapons used by theater
 - Weapons used by phase
 - Weapons used by weather state
 - Weapons used as a function of delivery profile
 - Inventory weapons not used
 - Weapons used by standoff class
 - Weapons used against each target class
- Platform
 - Weapons carried
 - Targets killed
 - Target value destroyed by phase
 - Attrition by phase range band, and delivery profile
 - Sortie utilization
 - Sortie aborts
 - Sorties flown by weapon type
 - Sorties flown by weather and phase
 - Sorties flown by attack profile and range band
 - Sorties flown by target class
- MTW
 - Total target value destroyed

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- Total platform attrition
- Total sorties flown by phase
- Target regeneration
- Target kills above minimum CINC target goals
- Target kills by range band.

III. MODEL FORMULATION AND MATHEMATICAL DESCRIPTION

This chapter contains the mathematical formulation of the model. For the most part, it reflects the computer code. One relevant deviation is the option in the code that is used when CPLEX cannot find a feasible solution. If this option is selected, then resources (aircraft, weapons, budget) are scaled up until a feasible solution is achieved. It was felt that adding this scaling factor to the description below would unnecessarily complicate the formulation.

A. INDICES

These following indices are used in the model:

a	delivery altitude
d	defense level
i	platform
j	weapon
k	time phase
m	major theater of war (MTW)
r	range band
s	service
t	target type
w	weather state (w = 1 is assumed to be "good" weather)

B. SETS

The following set is used in the model:

p(m)	set of time phases in MTW m
------	-----------------------------

C. DATA ELEMENTS

The following data elements are used in WORRM:

ABORT _{ijaktrw}	fraction of sorties aborted due to imperfect C4ISR
ACAVG _{im}	average number of platforms of type i available over the entire campaign in MTW m

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ACFT _{ik}	number of platforms of type i available in phase k
APS _{ijaktrwd}	attrition per sortie
ATMULT	multiplier for weighted platform attrition in the objective function
ATTBND _{im}	maximum fractional attrition allowed (of the quantity ACAVG _{im}) for platform i in MTW m
COST _j	unit cost for weapon type j (COST _i = 0 indicates that weapons of type j <u>cannot</u> be purchased)
DEGRADE _{ikw}	sortie rate degrade for platform i in phase k and weather state w
EKS _{ijatw}	expected kills per sortie
EKSADJ _{ijaktrw}	EKS degrade factor due to imperfect C4ISR
FRCD _{mtrd}	fraction of targets of type t located in range band r in MTW m that have defense level d
GOAL _{kt}	lower bound on the number of targets of type t to be cumulatively destroyed through phase k (in a specified MTW)
GOALRB _{ktr}	lower bound on the number of targets of type t to be cumulatively destroyed through phase k in range band r
INDATT	indicator specifying whether fractional attrition bounds are to be minimized or not (no = 0, yes = 1)
INDFLEX _t	weather flexibility indicator for targets of type t (no flex = 0 full flex = 1, partial flex = 2)
INDGOAL _t	indicates whether target kill goals for target type t are specified by time phase (value = 0) or by time phase and range band (value = 1)
INDVAL	indicator specifying whether target value destroyed is to be included in the objective function (no = 0, yes = 1)
RATE _{ik}	sortie rate for platform i in phase k

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$RGN_{t,kk,k}$	fraction of targets of type t destroyed in phase kk that regenerate in phase k [if $kk = k$, it includes the originally destroyed quantity as well (i.e., $RGN = 1 +$ fraction regenerated in the same period)]
$SRMULT$	multiplier for sorties flown in the objective function
SVC_i	service of platform i
$TARGET_{mtr}$	number of targets of type t in range band r and MTW m
$TGTVAL_{ktr}$	target value per target of type t destroyed in range band r during phase k
$TIME_k$	length of phase k
$TOTCOST$	total budget available for weapons purchases
$WEAP_{sj}$	stockpile of weapons of type j for platforms of service s (Note: this quantity is only used for those weapon types that <u>cannot</u> be purchased.)
$WEATHER_{kw}$	fraction of the time that weather state w applies in phase k
$WEIGHT_{im}$	value used to weight attrition of platform type i in MTW m
WPS_{ijr}	number of type j weapons delivered per sortie by platform i on range band r

D. VARIABLES

The decision variables of the model are listed below:

$ac_{ijaktrwd}$	platform assignments (i.e., thenumber of platforms of type i assigned to attack targets of type t under the given conditions
atk_{ktr}	number of targets of type t killed in phase k and range band r
$attrit_m$	multiplier for attrition bounds in theater m (used only if $INDATT = 1$)
buy_j	number of weapons purchased of type j

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frc_{ktr}	fraction of targets of type t killed (for the "first time") in phase k and range band r
tgt_{ktrw}	number of targets of type t killed in phase k , range band r , and weather state w
$tgtd_{ktrwd}$	number of targets of type t killed in phase k , range band r , weather state w , and defense level d

The following quantities are functions of the model variables, and are employed for ease of presentation. These quantities are often referred to as "passenger" variables.

$atr_{ijaktrwd}$	attrition of platforms involved in assignment $ac_{ijaktrwd}$
$sorties_{ijaktrwd}$	number of sorties flown by platforms involved in assignment $ac_{ijaktrwd}$
$tgtkill_{ijaktrwd}$	number of targets killed by platforms involved in assignment $ac_{ijaktrwd}$
usd_{msj}	number of weapons of type j used by platforms of service s in MTW m
$wpnugd_{ijaktrwd}$	number of weapons used by platforms involved in assignment $ac_{ijaktrwd}$

E. DERIVED QUANTITY

The following quantity is derived from other data as indicated:

$SRV_{ijaktrwd}$ = fraction of those platforms involved in assignment $ac_{ijaktrwd}$ that survive

$SRV_{ijaktrwd} = (1 - APS_{ijaktrwd}) ** POWER,$

where $POWER = RATE_{ik} * (1 - DEGRADE_{ikw}) * WEATHER_{kw} * TIME_k$

F. OBJECTIVE FUNCTION

The objective function is as follows:

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$$\begin{aligned} \max z = & \text{INDVAL} * \sum_{\text{ktr}} \text{TGTVAL}_{\text{ktr}} * \text{atk}_{\text{ktr}} - \text{INDATT} * M * \sum_m \text{attrit}_m \\ & - \text{ATMULT} * \sum_{m,i,j,a,k \in p(m),t,r,w,d} \text{WEIGHT}_{im} * \text{atr}_{ijaktrwd} \\ & - \text{SRMULT} * \sum_{ijaktrwd} \text{sorties}_{ijaktrwd} \end{aligned}$$

(Note: M is a large number, typically several hundred times the total target value contained in all theaters. This allows the user to minimize the attrition bounds while still allowing target value to influence the solution.)

This objective function allows the user to maximize target value destroyed, minimize attrition bounds, minimize weighted platform attrition, minimize sorties flown, or maximize a weighted combination of these quantities, as specified by the quantities INDVAL, INDATT, M, ATMULT, and SRMULT.

G. RELATIONSHIP BETWEEN DECISION AND PASSENGER VARIABLES

$$\text{atr}_{ijaktrwd} = (1 - \text{SRV}_{ijaktrwd}) * \text{ac}_{ijaktrwd}$$

$$\text{sorties}_{ijaktrwd} = \text{atr}_{ijaktrwd} / \text{APS}_{ijaktrwd}$$

$$\begin{aligned} \text{tgtkill}_{ijaktrwd} = & \text{sorties}_{ijaktrwd} * (1 - \text{ABORT}_{ijaktrw}) \\ & * \text{EKS}_{ijatw} * (\text{WPS}_{ijr} / \text{WPS}_{ij1}) \text{EKSADJ}_{ijaktrw} \end{aligned}$$

$$\begin{aligned} \text{wpnused}_{ijaktrwd} = & \text{sorties}_{ijaktrwd} * (1 - \text{ABORT}_{ijaktrw}) * \text{WPS}_{ijr} \\ & + \text{atr}_{ijaktrwd} * \text{ABORT}_{ijaktrw} * \text{WPS}_{ijr} \end{aligned}$$

The above equations express the relationship between platforms assigned, platforms attrited, sorties flown, targets killed, and weapons used. The fraction of platforms attrited is one minus the fraction of platforms surviving. The number of sorties flown is then the number of platforms attrited divided by the attrition per sortie.

The quantity EKS_{ijatw} gives the expected target kills per sortie for range band 1. It is assumed that the expected kills per sortie in any other range band are proportional to the weapon loadout in that range band divided by the loadout in the first range band. The number of targets killed is the number of unaborted sorties multiplied by the expected kills per sortie for the given range band times the EKS adjustment due to imperfect C4ISR.

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Finally, the number of weapons used is the sum of those expended in those sorties that find their target (i.e., unaborted sorties) and the weapons carried by those platforms that did not find their target and were then attrited.

H. CONSTRAINTS

1. Target Regeneration and Upper Bounds on Targets Attacked

$$\sum_{k \in p(m)} frc_{ktr} \leq 1$$

for all m, t, r

$$atk_{ktr} = \sum_{kk \in p(m), kk \leq k} frc_{kk,t,r} * RGN_{t,kk,k} * TARGET_{mtr}$$

for all m, t, r, k \in p(m)

The first set of constraints limits the total fraction of targets destroyed "for the first time" (i.e., before any regeneration) over a campaign to no more than the quantity that was originally present. The second set of constraints requires that the total number of targets destroyed in a particular time period and range band be the sum of the number of targets destroyed for the first time in the period and the targets that were destroyed earlier and regenerate in the period.

2. Lower Bounds on Targets Attacked

$$\sum_{kk \in p(m), kk \leq k, r} frc_{kk,t,r} * TARGET_{mtr} \geq GOAL_{kt}$$

for all m, k \in p(m), t \in INDGOAL_t = 0

$$\sum_{kk \in p(m), kk \leq k} frc_{kk,t,r} * TARGET_{mtr} \geq GOALRB_{ktr}$$

for all m, k \in p(m), r, t \in INDGOAL_t = 1

The first set of constraints ensures that target kill goals (expressed in terms of targets killed "for the first time") are met for those target types whose goals are specified by time phase. The second set of constraints does the same thing for those target types whose goals are specified by time phase and range band.

3. Relationships Among the Different Target Attack Variables

(atk_{ktr} , tgt_{ktrw} , and $tgtd_{ktrwd}$)

$$tgt_{ktrw} = WEATHER_{kw} * atk_{ktr}$$

for all $k, r, w, t \in IND FLEX_t = 0$

$$\sum_w tgt_{ktrw} = atk_{ktr}$$

for all $k, r, t \in IND FLEX_t = 1$

$$tgt_{ktr1} = WEATHER_{k1} * atk_{ktr}$$

and

$$\sum_{w \neq 1} tgt_{ktrw} = (1 - WEATHER_{k1}) * atk_{ktr}$$

for all $k, r, t \in IND FLEX_t = 2$

$$tgtd_{ktrwd} = FRCD_{mtrd} * tgt_{ktrw}$$

for all $m, k \in p(m), t, r, w, d$

The variables tgt_{ktrw} specify how the targets destroyed in a time phase (atk_{ktr}) are spread across weather states. For target types with $IND FLEX_t = 0$ (no weather flex), it is assumed that targets are destroyed uniformly over the phase, thus the number destroyed in a weather state is proportional to the fraction of time that the weather state occurs in the phase. The first set of constraints expresses this relationship.

The second set of constraints, for target types with $IND FLEX_t = 1$ (full weather flex), permits the targets destroyed in a phase to be distributed across weather states in any way desired (consistent, of course, with all other model constraints).

The next two sets of constraints are for target types with $IND FLEX_t = 2$ (partial weather flex). The number destroyed in the first weather state (good weather) must be proportional to the amount of time this weather state occurs in the phase. The number destroyed in the other weather states can be distributed across those states as desired (again, consistent with all other model constraints).

The last set of constraints specifies that the number of targets killed by defense level (for each target type, range band, and weather state) is proportional to the number of targets of that type with the given defense level in the specified range band.

4. Targets Killed

$$\sum_{ija} \text{tgtkill}_{ijaktrwd} = \text{tgtd}_{ktrwd}$$

for all k, t, r, w, d

These constraints ensure that the platform/weapon/delivery altitude assignments to a particular target type, range band, weather state, defense level, and time phase achieve the desired number of targets destroyed.

5. Platform Availability

$$\sum_{jatr d} \text{ac}_{ijaktrwd} + \sum_{j,a,k \in p(m), kk \leq k-l, t,r,d} \text{atr}_{i,j,a,kk,t,r,w,d} \leq \text{ACFT}_{ik}$$

for all i, m, k $\in p(m)$, w

Let $\text{SUMWX}_k = \text{no. of weather states such that } \text{WEATHER}_{kw} > 0$
 and $\text{W XFAC}_k = (\text{SUMWX}_k - 1) / \text{SUMWX}_k$

$$\sum_{jatr d} \text{ac}_{ijaktrwd} * (1 - \text{W XFAC}_k * \text{SRV}_{ijaktrwd}) + \sum_{j,a,k \in p(m), kk \leq k-l, t,r,w,d} \text{atr}_{i,j,a,kk,t,r,w,d} \leq \text{ACFT}_{ik}$$

for all i, m, k $\in p(m)$ such that $\text{W XFAC}_k > 0$

The first set of constraints ensures that the number of platforms assigned to any weather state during a time phase is no more than the average number of platforms available during the phase minus the number of platforms attrited in earlier phases.

Since platforms can be assigned to more than one weather state in a phase, another set of constraints is needed to further limit the number of platforms assigned to reflect not only the platform attrition during earlier phases, but also the platform attrition suffered during each weather state in the current time phase.

These constraints are derived as follows. If it is assumed that the weather states in a phase occur in a particular order (e.g., good weather first, marginal weather second, and adverse weather third), then it is straightforward to write a constraint for the platform assignment variables in the last-occurring weather state that reflects not only the platform attrition from previous time phases, but also the platform attrition from the earlier weather states in the current phase. If such a constraint is written for each possible ordering of the

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weather states, then the constraint shown above results by forming the average of these constraints.

6. Platform Attrition

$$\begin{aligned} &\text{If } \text{INDATT} = 0, \\ &\sum_{j,a,k \in p(m),t,r,w,d} \text{atr}_{ijaktrwd} \leq \text{ATTBND}_{im} * \text{ACAVG}_{im} \\ &\text{for all } i, m \end{aligned}$$

$$\begin{aligned} &\text{If } \text{INDATT} = 1, \\ &\sum_{j,a,k \in p(m),t,r,w,d} \text{atr}_{ijaktrwd} - \text{attrit}_m * \text{ATTBND}_{im} * \text{ACAVG}_{im} \leq 0 \\ &\text{for all } i, m \end{aligned}$$

If $\text{INDATT} = 0$, the total number of platforms of a given type attrited during the campaign is limited to the specified fraction of the average number of platforms available over the campaign. If $\text{INDATT} = 1$, then the variables attrit_m are the major contributors to the objective function and will produce allowable attrition fractions in each theater equal to the products $\text{attrit}_m * \text{ATTBND}_{im}$.

7. Relationship Between usd_{msj} and $\text{wpnugd}_{ijaktrwd}$

$$\begin{aligned} \text{usd}_{msj} &= \sum_{i \in \text{SVC}_i = s, a, k \in p(m), t, r} \text{wpnugd}_{ijaktrwd} \\ &\text{for all } m, s, j \end{aligned}$$

These equations express the fact that the total number of weapons of a given type used by a Service in an MTW is simply the sum over time phase, target type, range band, weather state, and defense level of the weapons used by platforms of the specified Service.

8. Total Cost Constraint

$$\sum_{j \in \text{COST}_j > 0} \text{COST}_j * \text{buy}_j \leq \text{TOTCOST}$$

This constraint limits the total amount spent on weapons purchases to the budget available.

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9. Upper Bounds on Weapons Used

$$\sum_m \text{usd}_{msj} \leq \text{WEAP}_{sj}$$

for all $s, j \ni \text{COST}_j = 0$

$$\sum_{ms} \text{usd}_{msj} - \text{buy}_j \leq 0$$

for all $j \ni \text{COST}_j > 0$

For weapons that cannot be purchased ($\text{COST}_j = 0$), the number of weapons used is limited to the stockpile available. For weapons that can be purchased ($\text{COST}_j > 0$), the number used is limited to no more than the number purchased.

IV. SPECIAL FEATURES

This chapter briefly describes several special features of the model that are not considered part of the core model and provides an overview of some C4ISR enhancements that have been used in several C4ISR studies.

A. MODIFICATION TO RESOURCES AVAILABLE

There are several special features relating to targets, weapons, and platforms. In DAWMS, the Services recommended removing some weapons and platform allocations to targets that were deemed unrealistic. A special feature was added that allowed each Service to provide exclusion files that would prevent some platforms and/or weapons from attacking some targets. For example, the A-10 could be precluded from attacking a particular target type that experience, doctrine, and training had proven was a bad match for that aircraft type. Similarly, the TLAM may be excluded from attacking a class of targets that operational planners for that system would avoid.

Other special constraints include:

- *Target Availability by Phase.* In some situations targets may go into hiding, making them difficult or impossible to attack with convention weapons either because they are hard to locate or they are in super hardened structures; a special set of constraints were developed to model these situations. In addition, target vulnerability could vary by phase. Thus, some targets could be made more difficult to kill in the build-up phase when they are "dug-in" and behind barriers.
- *Weapons by Service.* In this option, weapons cannot be shared between Services.
- *Weapons by MTW.* In this option, there are limits on the extent to which weapons can be transferred from the first MTW to the second MTW.

B. ALTERNATIVE OBJECTIVE FUNCTIONS

Several other special features modified both the objective function and some of the constraints. Most of these formulations were used to evaluate alternative force mixes.

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In all of these cases an initial set of runs established a reference target value and attrition level (in the form of an attrition bound). They include:

- *Minimize Attrition While Achieving a Specified Target Value.* This option is used to determine how much attrition increases as forces are removed or whether a new force can achieve the same warfight result (target value destroyed) while losing fewer aircraft.
- *Minimize the Increase in Weapons Budget.* In this formulation new constraints are added which mandate that the reference target value must be achieved without any change in attrition (bounds). As force structure is removed, the weapons budget is allowed to increase to compensate.
- *Minimize Additional Force Structure.* In this option, the force structure is reduced. Then a selected force structure element is allowed to increase to compensate for the decrease in capability. WORRM determines the smallest feasible increase in the selected force structure element (e.g., B-2s) that would achieve the original target value and attrition levels.

C. SEQUENTIAL OPTIMIZATION

Another recently added feature permits the model to perform sequential optimization. This allows the model to optimize period by period with the results of one period being inputs to the next. This feature was added because some felt that a global 2-MTW optimization provides too much "look ahead." That is, such a global optimization approach assumes too much knowledge on the part of the warplanner who could withhold weapons early, knowing there could be a better use for them later (perhaps in the other theater). On the other hand, a sequential optimization may encourage too much early "gratification," exhausting weapons that operational planners may hold in reserve. A realistic warplanner (and hence, analyst) will want to balance these two competing viewpoints.

D. C4ISR IMPROVEMENT

As mentioned earlier, WORRM has been used in a major C4ISR strike study sponsored by the Decision Support Center. In this formulation, the model adds a constraint that limits the number of targets that can be attacked using information generated by a C4ISR Processing, Exploitation, and Dissemination System (PEDS) network (target opportunities). A PEDS bin represents the capacities of different intelligence systems to process, exploit, and disseminate raw sensor data into target opportunities. A target location error is associated with each PEDS bin. Another

addition to the model puts a limit on the number of sorties that can use a particular C2 node. A C2 node is needed to communicate target information to the platform in a timely manner when attacking a mobile or short dwell target. This constraint reflects current estimates of Blue's ability to perform this function.

There is ongoing work that enhances this C4ISR analytic methodology. This study will assess the utility of the Discover II space-based MTI/SAR radar constellation to the JSEAD mission in the context of a major theater war. The general concept for this modeling problem is described in Figure 4 below.

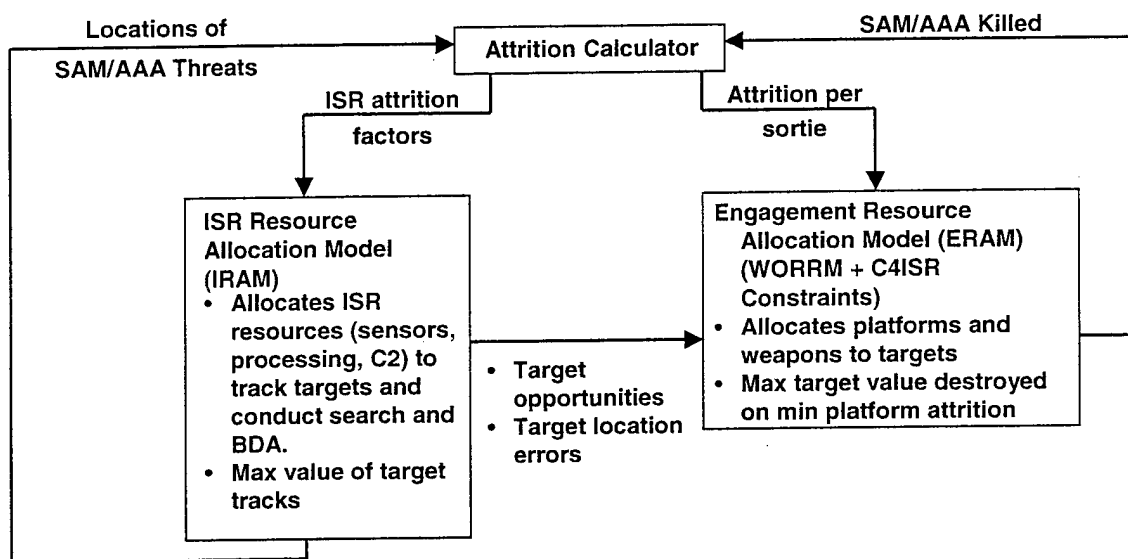


Figure 4. New C4ISR Modeling Construct

The reader should note that this C4ISR enhanced version of WORRM is now being called ERAM (Engagement Resource Allocation Model). The geometry is being modified to include sectors within range bands. ERAM will be run sequentially with 24 hour time steps. Weapon effectiveness will change at each time step to reflect the current estimate of target location error. This error together with data for the new constraints on target opportunities and on sorties due to C2 node limits are outputs of a new C4ISR optimization model called IRAM that is being developed at IDA. Basically, the IRAM model allocates sensors to cover areas and track targets, taking into account the limited number of sensor platforms and that the quality of data varies by sensor. The collected

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data is then processed with the processing capacity measured in terms of PEDS bins. This data is then communicated to the shooters through C2 constructs. The result is a number of attacks the C4ISR system can support against targets at varying levels of cueing and weapon effectiveness. This is ongoing work with more details available at a later date.

E. FINAL COMMENTS

In addition to this document, there is a classified paper prepared as part of DAS that describes in detail the WORRM database structure together with example data used in previous studies. It is available for authorized individuals. (See *Description of Selected WORRM Input Formations*, IDA, 30 December 1998.)

Finally, when comparing WORRM to other similar models in the DoD community, a few relative strengths are evident to us. They are the fidelity with which platform attrition is modeled, the treatment of C4ISR, and the modeling of weather effects on weapon effectiveness. (A more extensive description of this process is available - see *Deep Attack Weapons Mix Study--Part 1, WORRM Attrition Inputs*, IDA, June 1996.)

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Appendix A
GLOSSARY

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Appendix A
GLOSSARY

A/C	aircraft
ATACM	Army Tactical Missile System
BDA	battle damage assessment
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CALCM	Conventional Air Launched Cruise Missile
CBMR	Capabilities-Based Munitions Review
CEM	Combined Effects Munition
CINC	Commander in Chief
DAF	Dead-or-Alive Factor
DAS	Deep Attack Study
DAWMS	Deep Attack Weapons Mix Study
DIA	Defense Intelligence Agency
DPG	Defense Planning Guidance
ECM	electronic countermeasures
EO	Electro optical
ERAM	Engagement Resources Allocation Model
FLOT	forward line of troops
FW	fighter wing
IBFM	IDA Bomber Force Model
IR	infrared
IRAM	ISR Resource Allocation Model
ISR	intelligence, surveillance and reconnaissance
ITAM	IDA Target Accessibility Model

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JASSM	Joint Air-to-Surface Standoff Missile
JMEM	Joint Munitions Effectiveness Manual
JSEAD	joint suppression of enemy air defenses
JSOW	Joint Standoff Weapon
JSTARS	Joint Surveillance and Target Acquisition Radar System
MTW	major theater war
OUSDA(A&T)	Office of the Under Secretary of Defense (Acquisition and Technology)
PEDS	Processing, Exploitation and Dissemination System
P_k	probability of kill
SAM	surface-to-air missile
SEAD	suppression of enemy air defenses
SFW	Sensor Fuzed Weapon
SSPK	single-shot probability of kill
TACWAR	Tactical Warfare (Model)
TIF	Target Information Factor
TLAM	Tomahawk Land Attack Missile
TMD	Tactical Munitions Dispenser
TNF	Target Not Found
UAV	unmanned aerial vehicle
WCMD	Wind Corrected Munitions Dispenser
WMD	weapons of mass destruction
WORRM	Weapon Optimization and Resource Requirements Model

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13. ABSTRACT (Maximum 200 words) The Weapon Optimization and Resource Requirements Model (WORM) has been used in support of a number of studies. For example, earlier versions of the model were used in the FY95 Heavy Bomber Force Study, and in the Deep Attack Weapons Mix Study (DAWMS)—both the weapons mix and B-2 analyses. WORM is a one-sided campaign model, formulated as a linear program, which can be used to maximize target value destroyed, minimize platform attrition, or minimize a weighted combination of platform attrition, weapons used, and sorties flown. The model can also determine optimal inventory levels of specified weapon types, subject to a budget constraint. Principal inputs to the model include target damage goals, target distribution and defense coverage, platform arrival schedules, platform sortie rates, sortie effectiveness, weapon inventories, and platform attrition rates. Principal outputs include platform/weapon allocation to targets, target kills by platform and weapon type, platform attrition, weapons expended, and the optimal weapon mix. This model could serve as a complement to two-sided campaign analysis tools such as TACWAR and JWARS. This paper contains both a general description of the model that includes comments on data sources and its use in typical studies and an indepth treatment of its mathematical formulation.				
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